

# A SYSTEMATIC STUDY OF EFFECTS OF STELLAR ROTATION, AGE SPREAD AND BINARIES ON COLOR-MAGNITUDE DIAGRAMS WITH EXTENDED MAIN-SEQUENCE TURN-OFFS

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## ABSTRACT

Stellar rotation, age spread and binary stars are thought to be three most possible causes of the peculiar color-magnitude diagrams (CMDs) of some star clusters, which exhibit extended main-sequence turn-offs (eMSTOs). It is far from getting a clear answer. This paper studies the effects of three above causes on the CMDs of star clusters systematically. A rapid stellar evolutionary code and a recently published database of rotational effects of single stars have been used, via an advanced stellar population synthesis technique. As a result, we find a consistent result for rotation to recent works, which suggests that rotation is able to explain, at least partially, the eMSTOs of clusters, if clusters are not too old ( $< 2.0$  Gyr). In addition, an age spread of 200 to 500 Myr reproduces extended turn-offs for all clusters younger than 2.5 Gyr, in particular, for those younger than 2.2 Gyr. Age spread also results in extended red clumps (eRCs) for clusters younger than 0.5 Gyr. The younger the clusters, the clearer the eRC structures. Moreover, it is shown that binaries (including interactive binaries) affect the spread of MSTO slightly for old clusters, but they can contribute to the eMSTOs of clusters younger than 0.5 Gyr. Our result suggests a possible way to disentangle the roles of stellar rotation and age spread, i.e., checking the existence of CMDs with both eMSTO and eRC in clusters younger than 0.5 Gyr.

*Subject headings:* Stars: evolution — Hertzsprung-Russell (HR) and C-M diagrams — globular clusters: general

## 1. INTRODUCTION

Color-magnitude diagrams (CMDs) with extended main-sequence turn-offs (eMSTOs), which were observed by Hubble Space Telescope (HST) in the star clusters of the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), have received much attention in recent years. Such CMDs challenge the widely accepted thoughts of star clusters, i.e., simple stellar population (SSP) with a single age and metallicity (Mackey & Broby Nielsen 2007; Mackey et al. 2008; Milone et al. 2009; Piatti 2013; Girardi et al. 2009). Great efforts have been made to explain the observation. Many factors are thought to be the reasons for the observed eMSTOs, including a spread of chemical abundance (Mackey et al. 2008; Goudfrooij et al. 2009; Piotto et al. 2005, 2007), capture of field stars (Mackey et al. 2008; Goudfrooij et al. 2009), merger of existing star clusters (Mackey & Broby Nielsen 2007), formation of a second generation of stars from the ejecta of first generation asymptotic giant branch stars (D’Ercole et al. 2008; Goudfrooij et al. 2009), binary stars (e.g., Milone et al. 2009; Yang et al. 2011), observational selection and uncertainty effects (Keller et al. 2011), mixture of stars with and without overshooting (Girardi et al. 2011), differential reddening (Platais et al. 2012), age spread (e.g., Girardi et al. 2011; Rubele et al. 2011; Richer 2013), stellar rotation (e.g., Bastian & de Mink 2009), and combination of binaries and rotation (Li et al. 2012b). A spread of age (Milone et al. 2010; Girardi et al. 2011), rotation (Bastian & de Mink 2009), and a combination of rotation and binary (Li et al. 2012b) are finally thought of as three most possible causes of the special CMDs, although some against points are insisted by other works such as Mucciarelli et al. (2008), Goudfrooij et al. (2011a), Goudfrooij et al. (2011b), Glatt et al. (2008), Rubele et al. (2010), and Girardi et al. (2013). The work of Li et al. (2015a) indicates a degeneracy of the effects of stellar binarity and rotation.

Recently, many works have investigated the effects of some possible factors separately. **In particular, stellar rotation has been widely concerned (e.g., Yang et al. 2013; Li et al. 2014b; Jiang et al. 2014; Goudfrooij et al. 2014; Brandt & Huang 2015; Niederhofer et al. 2015; D’Antona et al. 2015; Bastian et al. 2016).** Yang et al. (2013) studied the effect of rotation on massive stars via their own stellar model. They concluded that rotation does not affect the CMD of star clusters younger than about 0.7 Gyr. A limitation of that work is that binary evolution was not taken into account, and a comparison to the effects of age spread and binaries was not made. However, an opposite conclusion was gained later by Brandt & Huang (2015), which took the stellar model of Georgy et al. (2013) and has considered gravity darkening. The works of Niederhofer et al. (2015) and D’Antona et al. (2015) also give support to the conclusion of Brandt & Huang (2015), but binary evolution was not taken into account either. Li et al. (2014b) declare that NGC1651 is a genuine simple stellar population from the observational thickness of the sub-giant branch, but Li et al. (2015a) and in particular, Li et al. (2015b) brought forward some doubts to it

according to the best-fit results based on detailed CMD comparisons. Correnti et al. (2014) also suggest that age spread can better explain some CMDs than rotation. **In this case, whether the peculiar CMDs of star clusters result from stellar rotation remains unclear (Bastian et al. 2016; Niederhofer et al. 2016).** More works on the causes of eMSTOs and stellar population types of star clusters are needed. In addition, most star clusters possibly contain a lot of binaries, and the effects of binary evolution, rotation and age spread are somewhat degenerated (Li et al. 2015a). Thereby, in order to explain the observed CMDs of star clusters in a right way, it is necessary to study the effects of stellar rotation, binary evolution, and age spread simultaneously. This work, therefore, revisits the effects of the above three factors on the CMDs of clusters with various ages. Besides the application of a new population synthesis technique (Li et al. 2015a), another improvement of this work is that a few thousand stars are assumed for each cluster, which leads to comparable star numbers to the most observed CMDs with eMSTO. Finally, the roles of stellar rotation, age spread, and resolved and unresolved binaries are shown clearly and compared to each other.

The layout of the paper is as follows: in section 2, we outline the model assumptions and computation techniques. Then we show the effects of rotation, binaries and age spread respectively in sections 3, 4 and 5. We finally conclude this work with section 6.

## 2. MODEL ASSUMPTIONS AND COMPUTATION TECHNIQUES

In order to model the CMDs of star clusters in detail, we use an advanced stellar population synthesis (hereafter ASPS) technique, which was brought forward by Prof. Zhongmu Li and has taken into account stellar binarity, rotation, star formation history and observational uncertainties simultaneously (Li et al. 2015b). The model assumptions and computation techniques are introduced as follows.

### 2.1. Initial Mass Function

Following some previous works (e.g., Li & Han 2008a,b; Li et al. 2012a, 2015a), we take the initial mass function (IMF) of Salpeter (1955) ( $\phi(m) \propto m^{-2.35}$ ) for stellar population models. This IMF is widely used in all kinds of stellar population synthesis studies. The lower and upper mass limits of stars are set to 0.1 and 100  $M_{\odot}$  respectively, as stars with masses out of this range are too faint or evolve too fast to be observed. Although the Salpeter IMF is not so accurate for low mass ( $< 1 M_{\odot}$ ) stars, it will not affect the result because only

bright CMD parts are used in this work.

## 2.2. Star Sample

We build up stellar populations based on a series of basic simple stellar populations (SSPs) with half single stars and half binaries. Each basic SSP contains 100 000 components. The star sample of basic populations is generated as follows. The mass of the primary component of a binary is generated following the selected IMF, and the mass of the secondary component is then calculated by taking a random secondary-to-primary mass ratio ( $q$ ), which obeys a uniform distribution within 0–1. Because eccentricity affects stellar evolution slightly (Hurley et al. 2002), a random eccentricity ( $e$ ) within 0–1 is assigned to each binary. The separations ( $a$ ) of two binary components are given by a simple shape:

$$an(a) = \begin{cases} \alpha_{\text{sep}}(a/a_0)^m & a \leq a_0; \\ \alpha_{\text{sep}}, & a_0 < a < a_1, \end{cases} \quad (1)$$

where  $\alpha_{\text{sep}} \approx 0.070$ ,  $a_0 = 10R_{\odot}$ ,  $a_1 = 5.75 \times 10^6 R_{\odot} = 0.13\text{pc}$  and  $m \approx 1.2$  (Han et al. 1995). This process leads to about 50 per cent binaries with orbital periods less than 100 yr in a simple population. We call such simple populations basic models and build up other stellar populations based on these models. This method is used by many previous works, e.g., Zhang et al. (2004) and Li & Han (2008a).

Because binary fraction is different for various star clusters, we build stellar populations with different binary fractions. In a simple way, we change the binary fraction of a population by removing some random single stars or binaries from basic models. This allows one to build stellar populations with arbitrary binary fraction between 0 and 100 per cent easily. Note that all stars with orbital periods larger than 100 yr are considered as single stars, as their components hardly exchange mass in their evolution (Hurley et al. 2002).

## 2.3. Stellar Evolution

After the generation of star sample, we evolve all stars using the rapid stellar evolution code of Hurley & Tout (1998) and Hurley et al. (2002) (Hurley code). This code calculates the evolution of stars using some fitting formulae, which are based on the stellar models computed by Pols et al. (1998). Many stellar evolutionary parameters, e.g., effective temperature, surface gravity, and luminosity, can be computed by Hurley code. There are two advantages to take Hurley code for this work. First, both the evolution of single and binary stars can be calculated via this code. Most binary interactions such as mass transfer,



mass accretion, common-envelope evolution, collisions, supernova kicks, angular momentum loss mechanism, and tidal interactions are taken into account in its binary evolution mode. Second, it allows one to calculate the evolution of stars much faster than traditional stellar evolutionary codes, but with enough accuracy (less than 5 per cent in stellar luminosity, radius and core mass) for population synthesis works. Some default parameters of Hurley code, which have been tested by Hurley & Tout (1998) and Hurley et al. (2002), are used for this work. Because binary evolution changes both the evolutionary tracks and main-sequence lifetimes of stars and will directly change the CMDs of star clusters, it is necessary to include binary evolution in CMD studies. We will be shown that binary evolution is helpful for understanding the eMSTOs of clusters younger than 0.5 Gyr because some scatter stars form in this evolution mode. Therefore, it is appropriate to choose Hurley code for this work. For convenience, a metallicity of  $Z = 0.008$  is taken for simulated clusters.

## 2.4. Treatment of Stellar Rotation

Hurley code does not take stellar rotation into account, so we add the effect of rotation on effective temperature and luminosity to some stars in the mass range of  $1.6 \sim 15 M_{\odot}$  when necessary. It makes us able to study star clusters younger than about 2 Gyr, in which CMDs with eMSTO are usually observed. Because the database of Georgy et al. (2013) does not include stars less massive than  $1.7 M_{\odot}$ , the effect of rotation on stars between 1.6 and  $1.7 M_{\odot}$  is simply interpolated by assuming zero effect for  $1.6 M_{\odot}$ . However, in order to give a reliable conclusion, only the results of clusters younger than 1.7 Gyr are used for this paper.

### 2.4.1. Inclusion of Rotation Effect

A recent result of Georgy et al. (2013) is chosen for calculating the effect of rotation, because this database is particularly designed for constructing synthetic stellar populations. The database is derived from the Geneva code, which includes a full parameterization of angular momentum transport and wind loss. This database has been used by many previous works such as Li et al. (2015a) and Brandt & Huang (2015). The procedure to include rotation effect is as follows. First, the changes of surface temperature and luminosity, which are caused by stellar rotation, are calculated by comparing the evolutionary tracks of rotating stars to those of their non-rotating counterparts. These changes depend on metallicity, mass, rotation rate and age. Then such changes are added to the evolutionary parameters of non-rotating stars, which are computed via Hurley code. A limitation in the database of Georgy et al. (2013), i.e., the stellar mass range of  $1.7 \sim 15 M_{\odot}$ , should be noted, as it

makes us unable to study the rotational effect on clusters older than about 1.7 Gyr reliably. Because the database of Georgy et al. (2013) does not contain the cases for some masses, metallicities, rotation rates, and ages, the original values are interpolated to match our needs. Note that the effect of rotation on the main-sequence lifetimes of stars is naturally included in our treatment. The reason is that the database of Georgy et al. (2013) has given the change of evolutionary parameters caused by rotation at various ages. The changes of main-sequence lifetimes can be described by the evolutionary parameters. For example, on the Hertzsprung-Russell (HR) diagram, a rotating star will be shown to get a turn-off point at an older age compared to its non-rotating counterpart. Thereby, when we correct for the evolutionary parameters of rotating stars, the effect of rotation on main-sequence lifetime has been included. However, unlike the work of Brandt & Huang (2015), gravity darkening has not been accounted in this work. According to a test of Dr. Timothy D. Brandt (later Brandt), this affects our result slightly, although gravity darkening leads to a small extra extension of turn-offs.

#### 2.4.2. *Rotation Rate Distribution*

In order to calculate the effects of stellar rotation on the synthetic CMDs of simulated star clusters properly, we need to assume a distribution of stellar rotation rate ( $\omega = \Omega/\Omega_{\text{crit}}$ ) (RRD), which affects the CMD parts near MSTO obviously. Fortunately, the works of Royer et al. (2007) and Zorec & Royer (2012) have determined the statistical distributions of B9–F2 type stars. This enables us to assign random rotation rates to the member stars of a population directly following some observational distributions rather than a theoretical one. For the sake of convenient use of the observed distributions, we fitted the results of Royer et al. (2007) (hereafter Royer distribution) via some polynomial functions (see Fig. 1 and Table 1) and then use these functions to represent the RRDs of B9–F2 stars. The comparison of fitting distributions to the original results of Royer et al. (2007) indicates that these fitting functions can reproduce the observed distributions accurately. Stars of earlier types than B9 ( $> \sim 2.5M_{\odot}$ ) are assumed to have the same RRD as the Royer result for B9 stars. An obvious trend is that the fraction of stars decreases quickly with increasing rotation rate for  $\omega > 0.7$ . This means that there are only a small fraction of stars with  $\omega > 0.7$ . Note the results will be similar if the more recent result of Zorec & Royer (2012) is used instead of Royer et al. (2007), because these two works, in fact, give similar distributions for the stellar rotation rate and rotational velocity of stars.

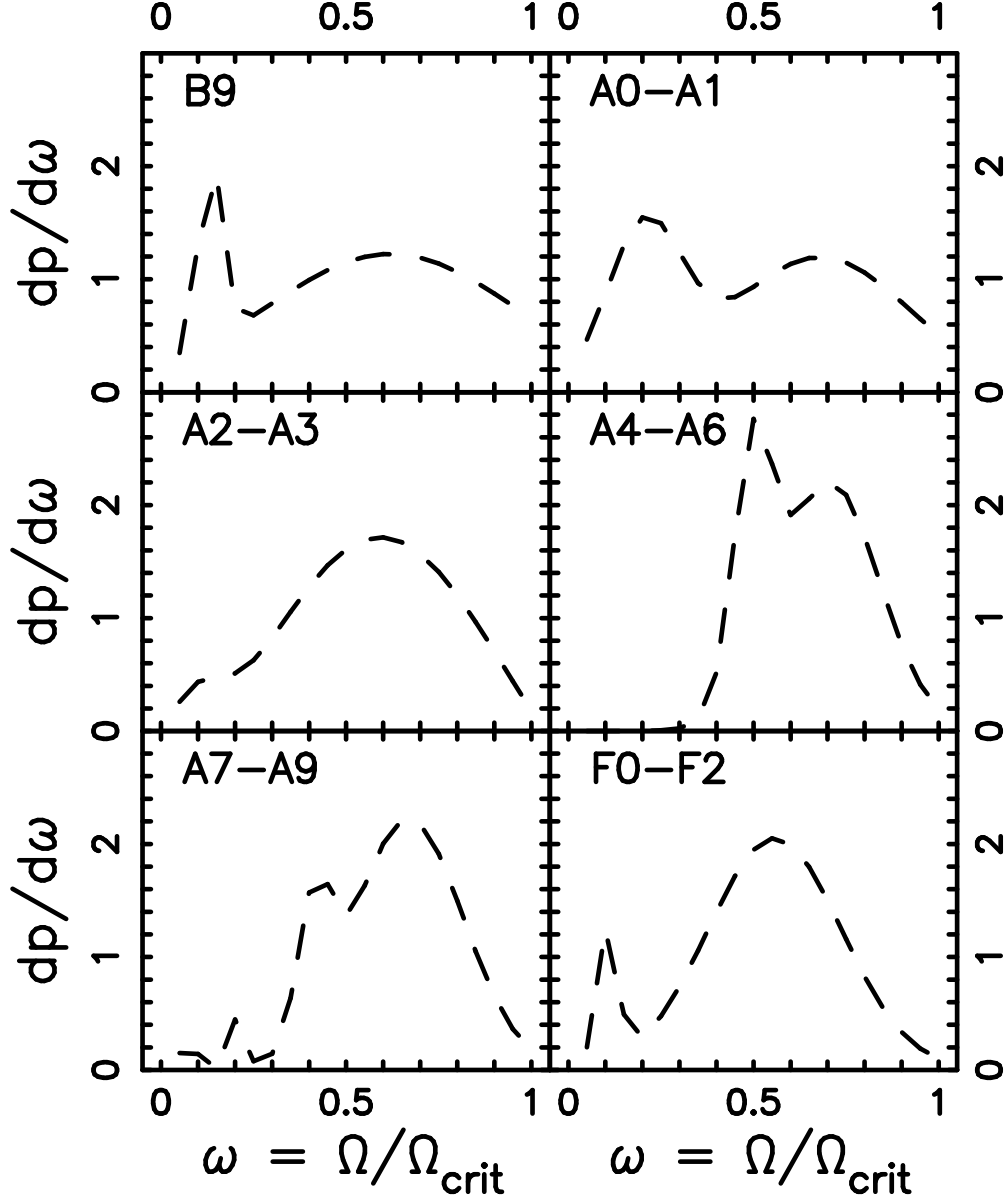


Fig. 1.— Fitting distributions of rotation rates ( $\omega \geq 0.05$ ) of B9–F2 type stars. The fitting formulae are based on the result of Royer et al. (2007), and are described by Table 1.  $p$  and  $\omega$  are star fraction and rotation rate respectively. The paper uses the B9 distribution for more massive stars.

## 2.5. Atmosphere Library

The stellar evolutionary parameters ( $[\text{Fe}/\text{H}]$ ,  $T_{\text{eff}}$ ,  $\log g$ ,  $\log L$ ) are transformed into colors and magnitudes via the atmosphere library of Lejeune et al. (1998) (BaSeL). Because this wide-wavelength band coverage (including the well used  $B$ ,  $V$ ,  $I$  and  $K$ ) library was well calibrated and has been widely used in a good deal of research works, it is an excellent choice for this work.

## 3. EFFECT OF STELLAR ROTATION

It is necessary to check the reliability of the treatment of stellar rotation first, as the combination of results of Hurley et al. (2002) and Georgy et al. (2013) is used. Our test finally shows that the treatment of rotation in this work is in well agreement with other works, e.g., Brandt & Huang (2015). Fig. 2 shows a CMD of a simulated cluster with  $Z = 0.08$  and 1.0 Gyr. The RRD of Royer et al. (2007) is taken for this cluster and all stars are assumed to be single stars. We see that this CMD is close to the result of Brandt & Huang (2015).

Figs. 3-10 then show the effect of rotation on the CMDs of simulated star clusters with various ages from 0.2 to 1.7 Gyrs. Three binary fractions ( $f_b = 0.3, 0.5$  and  $0.7$ ) are taken for clusters on account of the existence of binaries in most young and intermediate-age clusters (e.g. Elson et al. 1998). In addition, we vary rotator fraction ( $f_r$ ) from 0 to Royer distribution because some star clusters without eMSTO have been observed, and such clusters may contain less rotating stars than the result of Royer et al. (2007). In fact, the RRD of stars in the LMC clusters is unknown, and it is possible that some star clusters include more rotating stars than the observation of Royer et al. (2007). We therefore enlarge the fraction of stars with large rotation rate by taking a Gaussian distribution with mean and standard deviation of 0.7 and 0.1 for rotation rate (hereafter Gaussian distribution). As a whole, four rotator fractions ( $f_r$ ), i.e., 0, 0.5 Royer, Royer, and Gaussian are finally adopted for simulated star clusters. The models with  $f_r = 0$  contain no rotating stars. Those with  $f_r = 0.5$  Royer contain half non-rotating stars and half stars with rotation rates following Royer distribution. For the case of  $f_r = \text{Royer}$ , all stars obey Royer distribution. Taking various rotator fractions will produce various kinds of CMDs, and this is helpful for understanding the role of rotation clearly. In order to enable readers to compare the figures, Figs. 3-10 are plotted with the same size. Observational errors are not considered to avoid their confusion.

Figs. 3 and 4 show the effect of rotating stars on the CMDs of young (0.2 and 0.4 Gyrs) star clusters. When binary fraction is small (0.3), stellar rotation leads to only a narrow

Table 1: Fitting formulae for rotation rate distributions (RRD) of B9 to F2 type stars. All distributions are described by  $\frac{dp}{d\omega} = f_0 + \sum \frac{a_i}{w_i} \cdot \exp(-2 * (\frac{\omega - c_i}{w_i})^2)$ , where  $p$  is star fraction and  $\omega$  is rotation rate.

Type	$f_0$	$a_1$	$w_1$	$c_1$	$a_2$	$w_2$	$c_2$
B9	0	0.91994	0.85301	0.62004	0.11451	0.07828	0.13371
A0-A1	0	0.29196	0.25220	0.20447	0.61923	0.61374	0.67926
A2-A3	-0.99083	0.12616	0.22893	0.06704	1.99339	0.84887	0.59142
A4-A6	0	0.21978	0.12983	0.49718	0.60092	0.33494	0.70526
F0-F2	0	0.06730	0.06988	0.10557	0.75391	0.45133	0.55747
	$f_0$	$a_1$	$w_1$	$c_1$	$a_2$	$w_2$	$c_2$
A7-A9	0	0.02195	0.02689	0.07478	0.01771	0.03942	0.20553
		$a_3$	$w_3$	$c_3$	$a_4$	$w_4$	$c_4$
		0.10796	0.08934	0.41528	0.65859	0.29589	0.66827

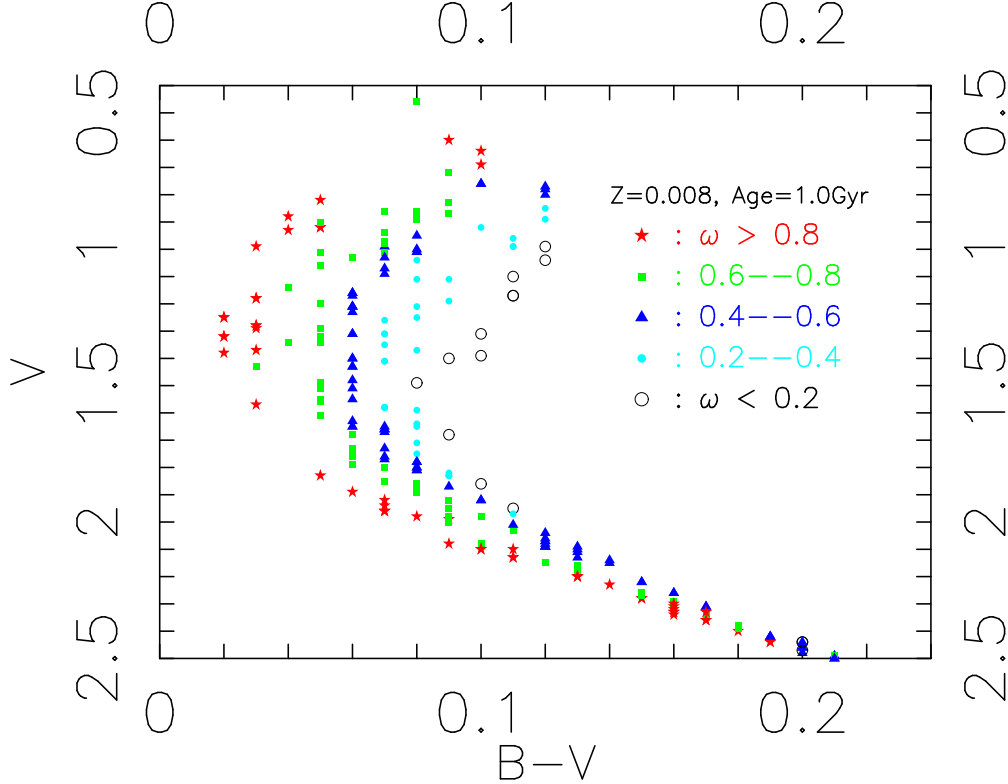


Fig. 2.— Synthetic CMD of a single star stellar population with metallicity ( $Z$ ) of 0.008 and age of 1 Gyr. The rotation effect of stars more massive than  $1.6 M_{\odot}$  is considered. All stars are assumed to follow the RRD of Royer et al. (2007).

eMSTO for clusters of 0.2 Gyr, while it extends the MSTO of clusters of 0.4 Gyr more. At the same time, binaries (including both resolved and unresolved ones) supply significant extension on the turn-off of such clusters. Obvious eMSTO structures are formed by including a large fraction (e.g., 0.7) of binaries. In particular, eMSTOs become clearer when both binaries and rotating stars are included.

Figs. 5 and 6 give the result for some clusters with ages of 0.5 and 0.8 Gyrs. We see that rotation results in eMSTOs. The extension of MSTO is obviously larger than the cases of 0.2–0.4 Gyrs and it increases with stellar age. Moreover, the extension of MSTO seems very sensitive to RRD. The second case of rotation,  $f_r = 0.5$  Royer, leads to the largest extension. Binaries are shown to be much less important to form eMSTO, although a few scatter stars are generated from binaries.

Figs. 7 and 8 present the results for 1.0 and 1.2 Gyr-old simulated clusters. The CMDs of populations with rotators become significantly different from those of populations of non-rotating stars. If only the effect of binary stars (including resolved and unresolved binaries) is taken into account, MSTOs are very thin (top panels), although some scatter stars (e.g., blue stragglers and red stragglers) are generated. The turn-offs become significantly thick when some rotators are included in star clusters. In particular, maximum eMSTOs are observed in clusters containing half rotating stars following the RRD of Royer et al. (2007). Large eMSTOs can also be observed when taking Royer distribution for all stars. One can look at the two middle lines of Figs. 7 and 8 for the details. For these clusters, their CMD parts near turn-off look like “golf-club” (Girardi et al. 2011), in which the part above turn-off point is wider than the lower part in color direction. The synthetic CMDs are similar to those observed in many star clusters, e.g., NGC1399.

Figs. 9 and 10 show the cases of simulated clusters with ages of 1.5 and 1.7 Gyrs. Similar to previous figures, we are shown that stellar rotation is able to generate eMSTOs. However, the extension of MSTOs becomes smaller compared to clusters with ages around 1.1 Gyr (Figs. 7 and 8).

It is event from the above results that overall stellar rotation have some effects on the CMDs of clusters between 0.2 and 1.7 Gyr, but the effect depends on stellar age. The effect of rotation on MSTO increases with age from 0.2 to about 1.2 Gyr, then it decreases with increasing age. The result is similar to the work of Brandt & Huang (2015). Rotation makes both the turn-off and main sequence near turn-off wider than the non-rotating case. For simulated clusters with ages between 1.0 and 1.5 Gyr, the CMD part including turn-off and main sequence looks like a “golf-club” (see, e.g., 0.5 Royer), which is similar to the observed results of many clusters, e.g., NGC 1651, NGC 1868, and NGC 1399. Therefore, stellar rotation is able to reproduce, at least partially, the eMSTOs of star clusters. Our

conclusion agrees well with the works of Brandt & Huang (2015), D’Antona et al. (2015) and Niederhofer et al. (2015), but is partially different from Yang et al. (2013). The different conclusion of Yang et al. (2013) for young clusters possibly results from their stellar evolution model. Note that if gravity darkening effect is considered, the results will be more similar to the observed CMDs, because gravity darkening effect can slightly extend MSTOs, according to the test of Brandt.

From this work, we find that the role of rotation depends on many factors, e.g., stellar evolution model, RRD and the mass range of rotating stars. In more detail, some opposite results will be obtained from the stellar evolution models of Yang et al. (2013) and Georgy et al. (2013). RRD affects the CMD shapes of simulated clusters significantly (see Figs. 6–8), and considering stars less massive than  $1.7 M_{\odot}$  or not leads to various roles of rotation for clusters older than about 1.7 Gyr. This therefore calls for more works on these factors, in order to unfold the stellar populations of star clusters with eMSTOs. However, gravity darkening does not significantly affect our main conclusions.

#### 4. EFFECT OF BINARY STARS

Some previous works (e.g., Li et al. 2014b, 2015a) have mentioned that binary star is not the main cause of eMSTOs, but no work supplies a clear figure about the effects of different types of binaries. This section gives an answer via Figs. 3–10. Figs. 3 and 4 suggest that resolved and unresolved binaries may contribute to the eMSTOs of young ( $< 0.5$  Gyr) clusters. Binary stars lead to some blue stragglers (scatters on the upper left of turn-off, e.g., BS in Fig. 3), red stragglers (scatters on the lower right of turn-off, e.g., RS in Fig. 3), and scatter stars above the turn-off (e.g., Figs. 9 and 10). However, the role of binaries depends on stellar age. For clusters older than 0.5 Gyr, scatter stars from binaries affect the turn-off shape very slightly (Figs. 5–10). This implies that binaries is certainly not the main cause of eMSTO of most intermediate-age clusters. As a part of binaries, resolved or interactive binaries are correspondingly not the main cause of eMSTO. The top panels of Figs. 9 and 10 show the effect of unresolved binaries in a clearer way. It is obvious that unresolved binaries (black stars in region “A”) make the MS wider compared to a population of single stars (red points), as some unresolved binaries locate on the right of MS. In addition, a few unresolved binaries locate above the turn-off (region “B”). However, the turn-off structure of a population of non-rotating binaries is obviously different from the observed CMDs, because such binary populations contain few stars in region “C” but many stars are observed in star clusters with peculiar CMDs. Such stars are actually an important part of eMSTOs. Therefore, binaries, including interactive binaries, resolved binaries, and

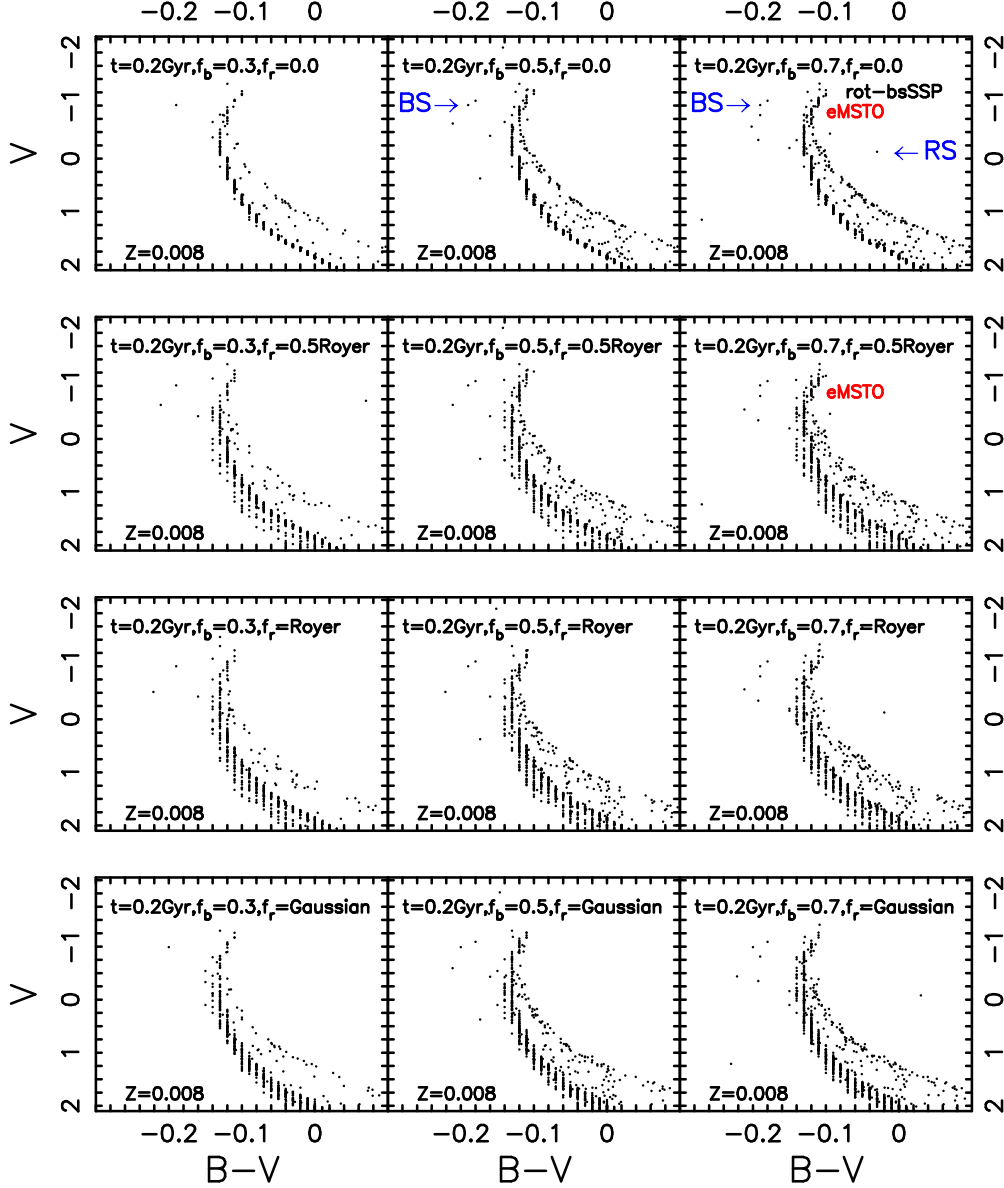


Fig. 3.— Effects of rotating stars and binaries on CMDs of simulated star clusters. Color and magnitude are in mag. All clusters have the same metallicity ( $Z = 0.008$ ) and age (0.2 Gyr). Stars of each cluster (about 6000 stars) formed in a single star burst. Binary fractions ( $f_b$ ) in left, middle, and right columns are 0.3, 0.5 and 0.7 respectively. From top to bottom, the fraction of rotating stars ( $f_r$ ) increases. “rot-bsSSP” means SSP with a fraction of rotating stars (including binary and single stars). “eMSTO” denotes extended main-sequence turn-offs. “BS” and “RS” mean blue stragglers and red stragglers. Binaries closer than 2500 AU are assumed to be unresolved. This separation corresponds to  $0.05''$  (approximately *HST* resolution) at a distance of 50 kpc.



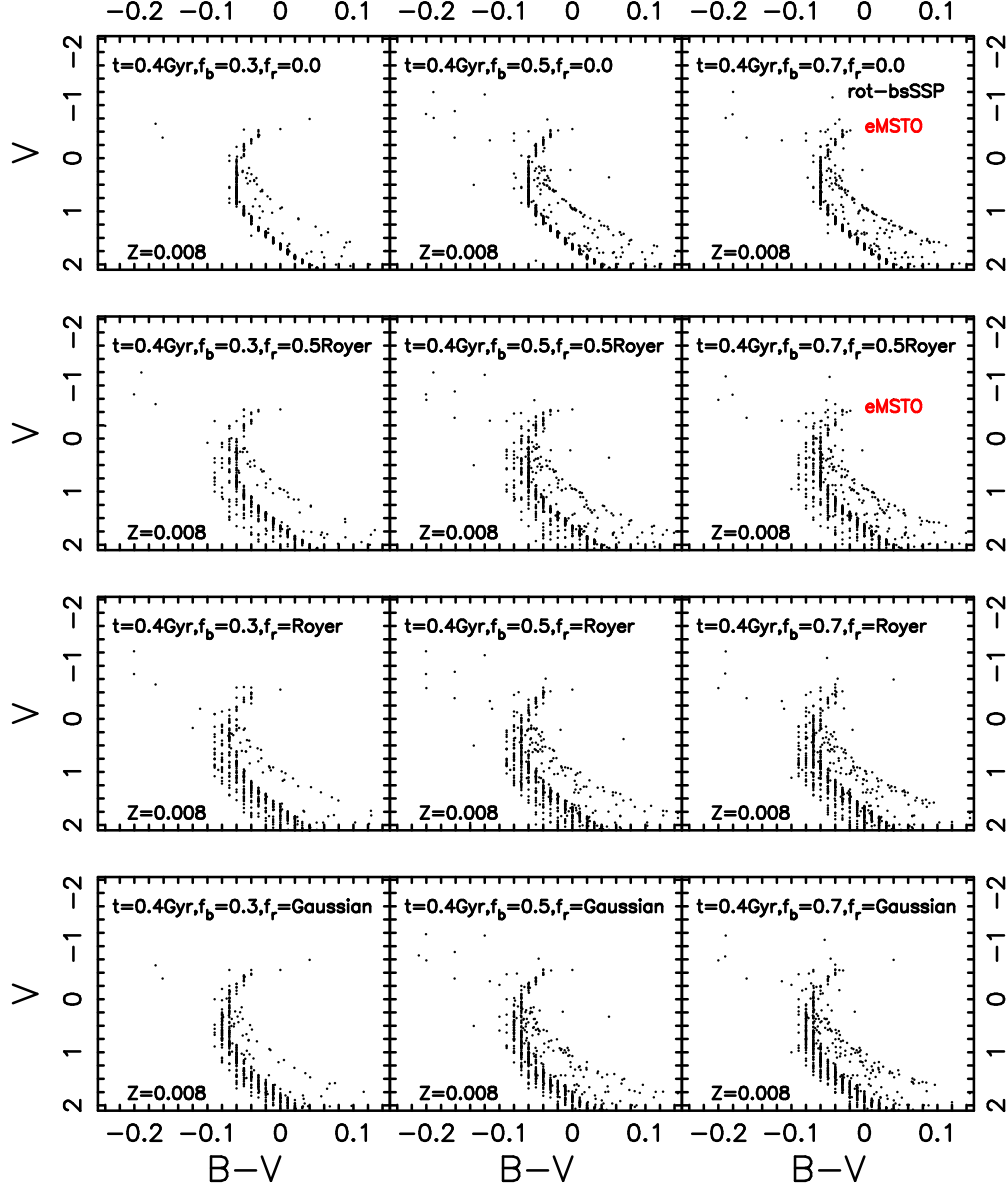


Fig. 4.— Similar to Fig. 3, but for simulated star clusters with the age of 0.4 Gyr.

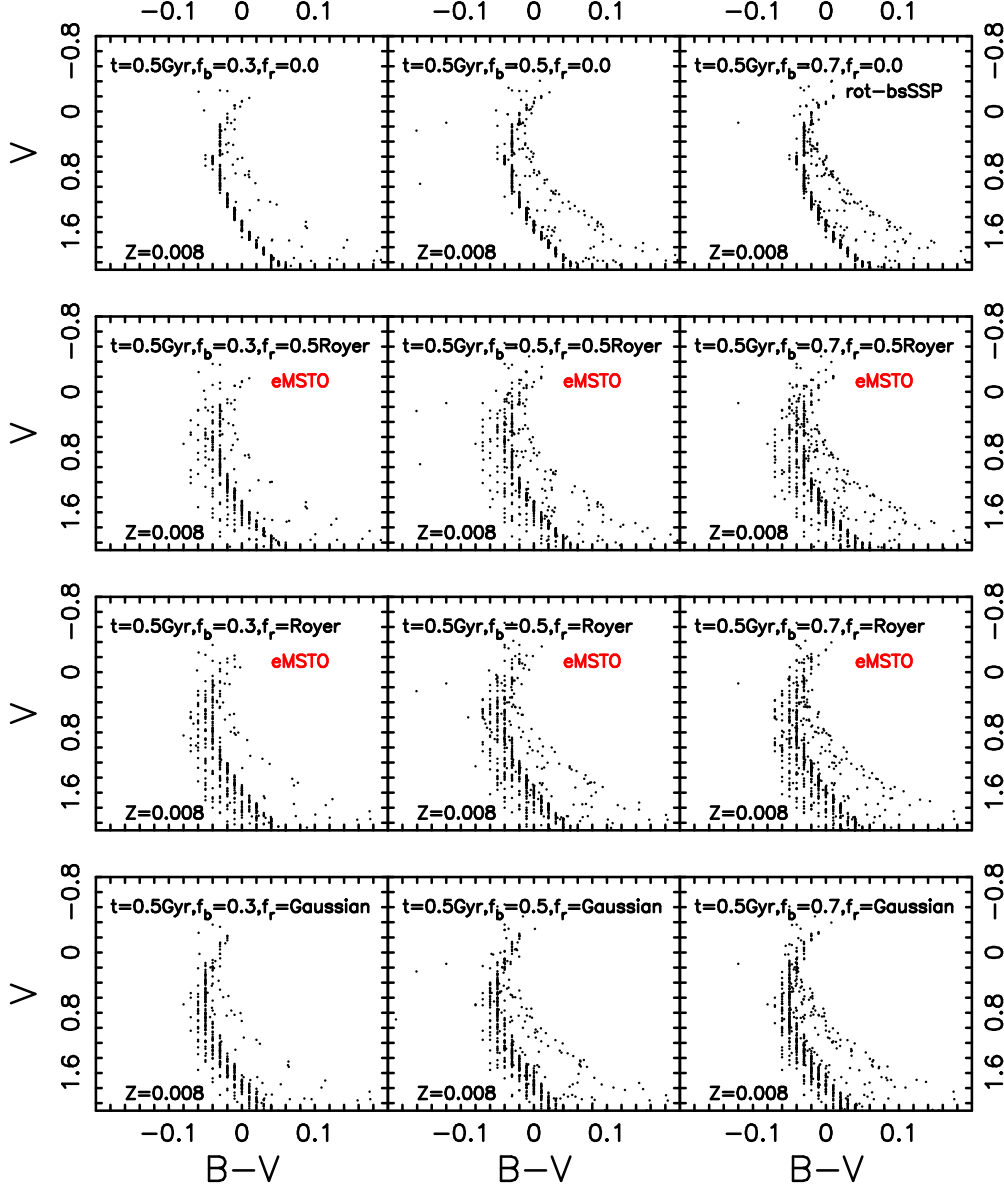


Fig. 5.— Similar to Fig. 3, but for simulated star clusters with the age of 0.5 Gyr.

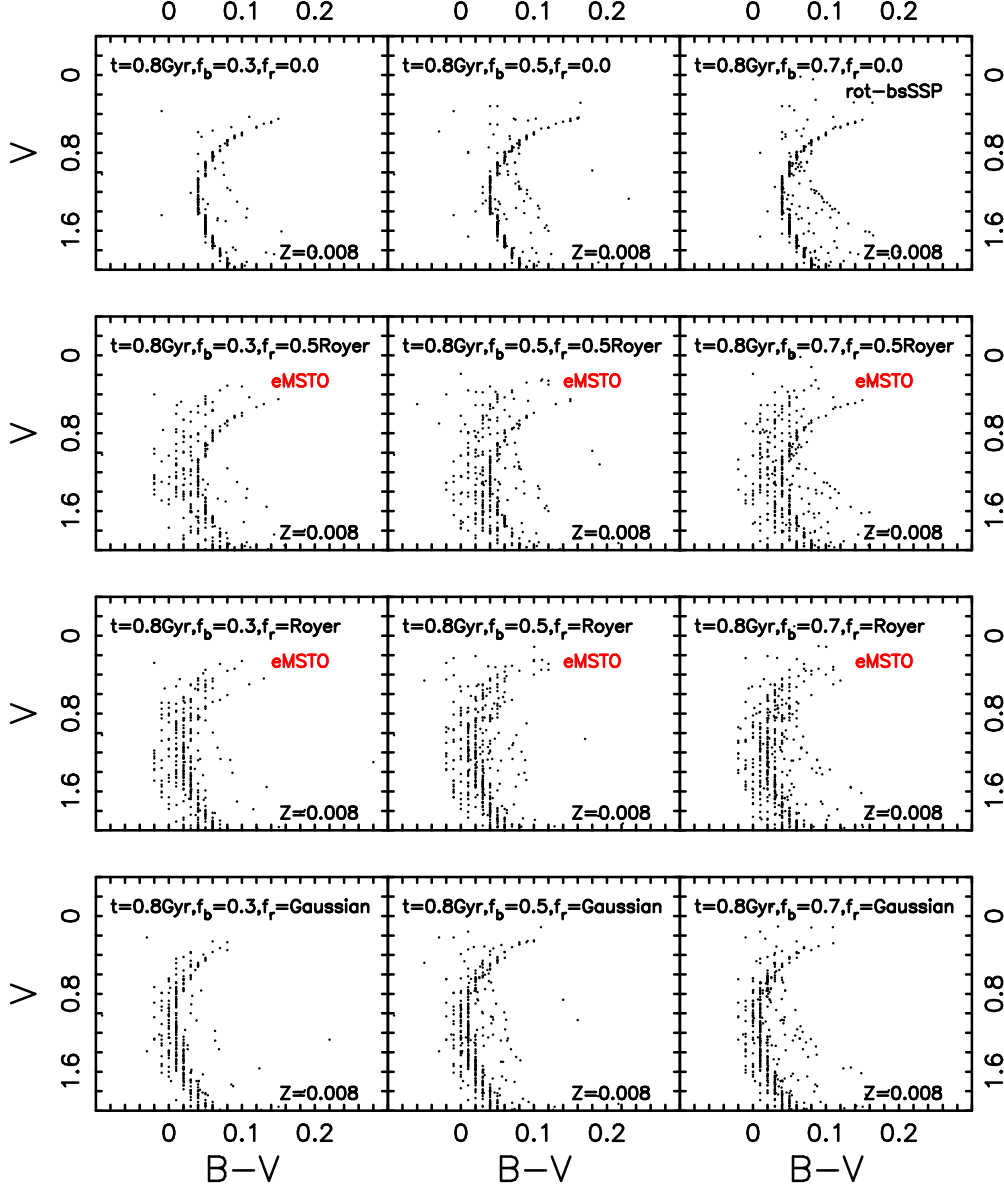


Fig. 6.— Similar to Fig. 3, but for simulated star clusters with the age of 0.8 Gyr.

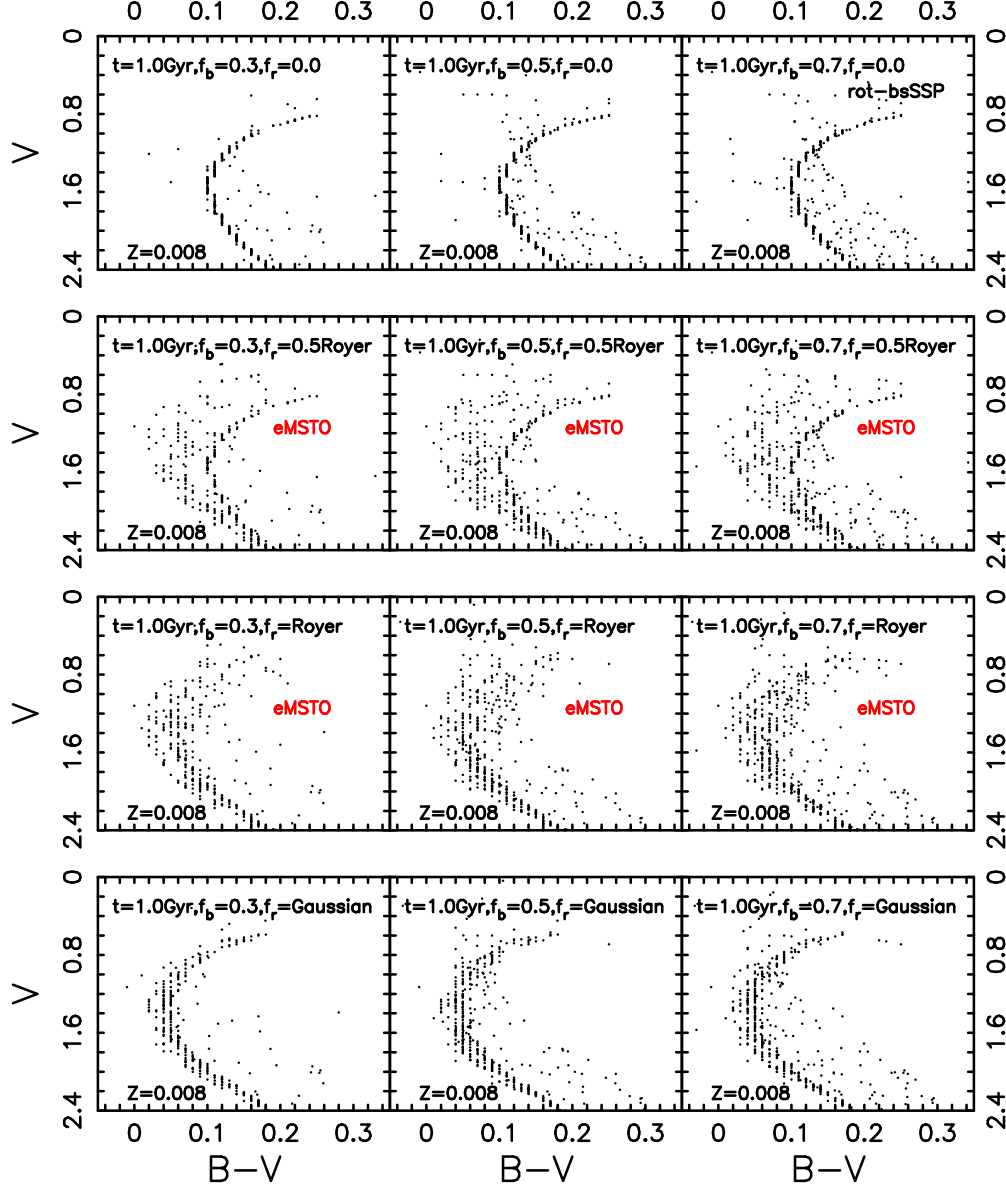


Fig. 7.— Similar to Fig. 3, but for simulated star clusters with the age of 1.0 Gyr.

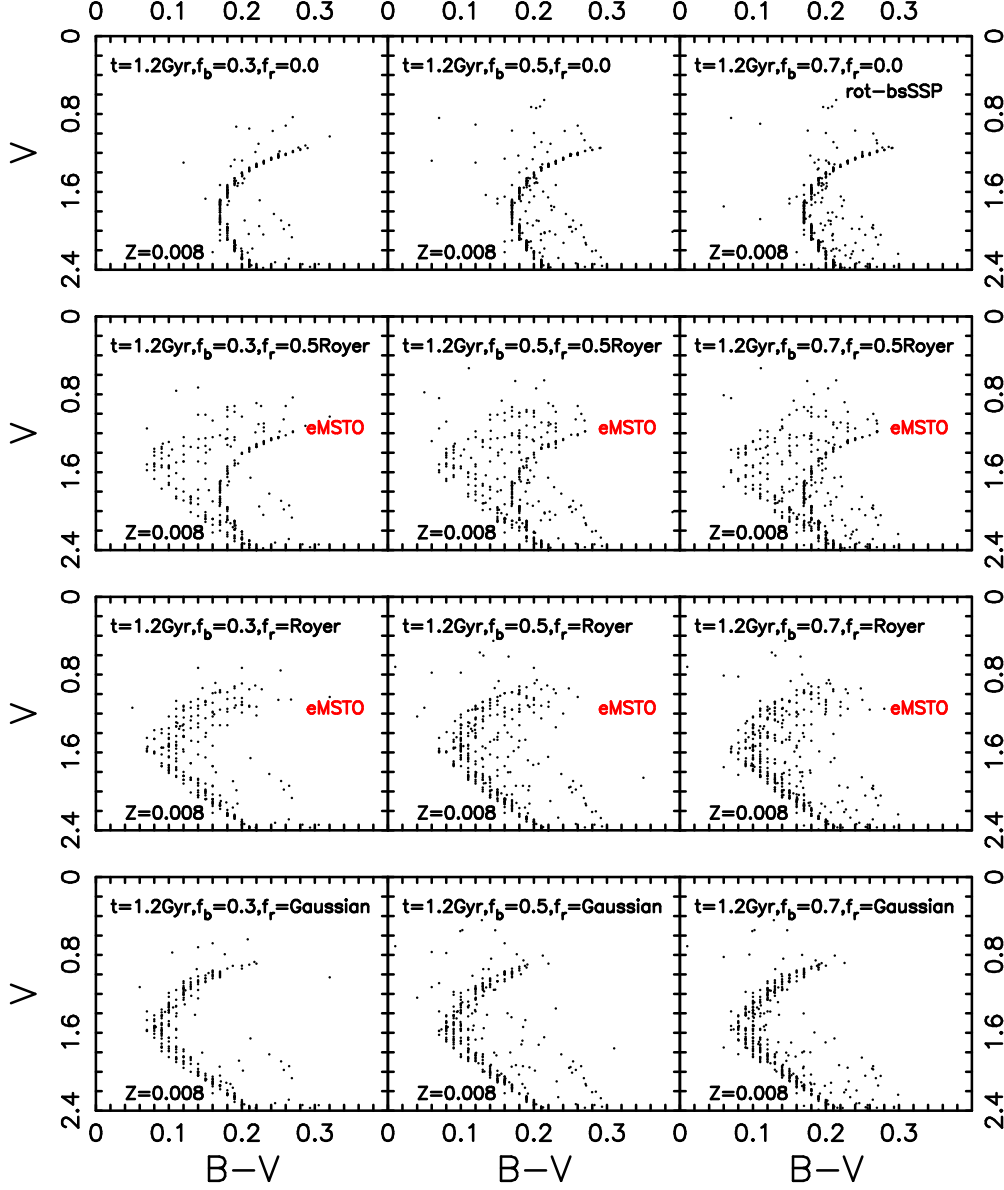


Fig. 8.— Similar to Fig. 3, but for simulated star clusters with the age of 1.2 Gyr.

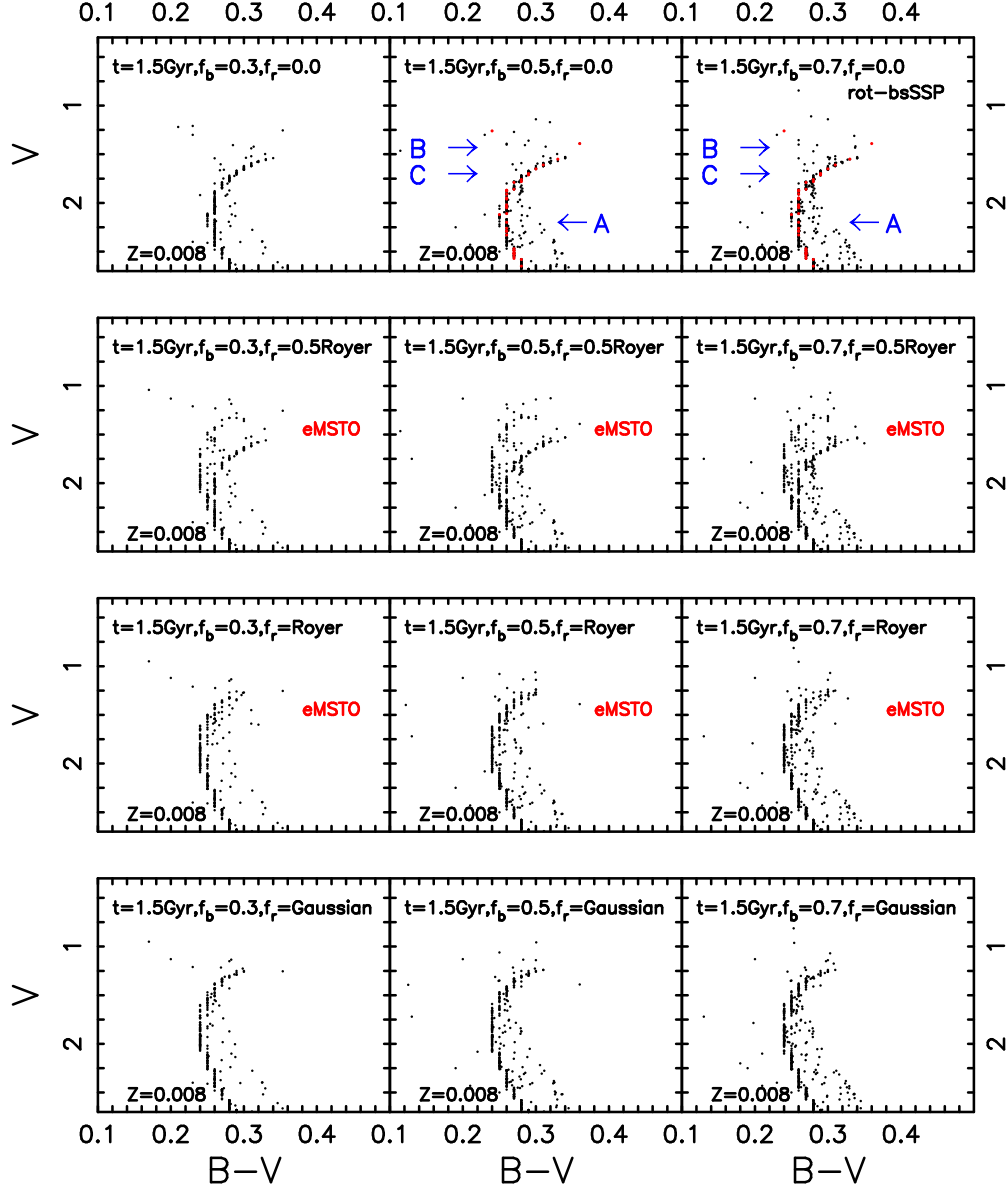


Fig. 9.— Similar to Fig. 3, but for simulated star clusters with the age of 1.5 Gyr. Region A is an extension of MS that is caused by unresolved binaries. Region B consists of scatter stars that form from unresolved binaries. Region C is a part that is different from observed eMSTO CMDs. Red points represent the CMD of a stellar population without any binaries.

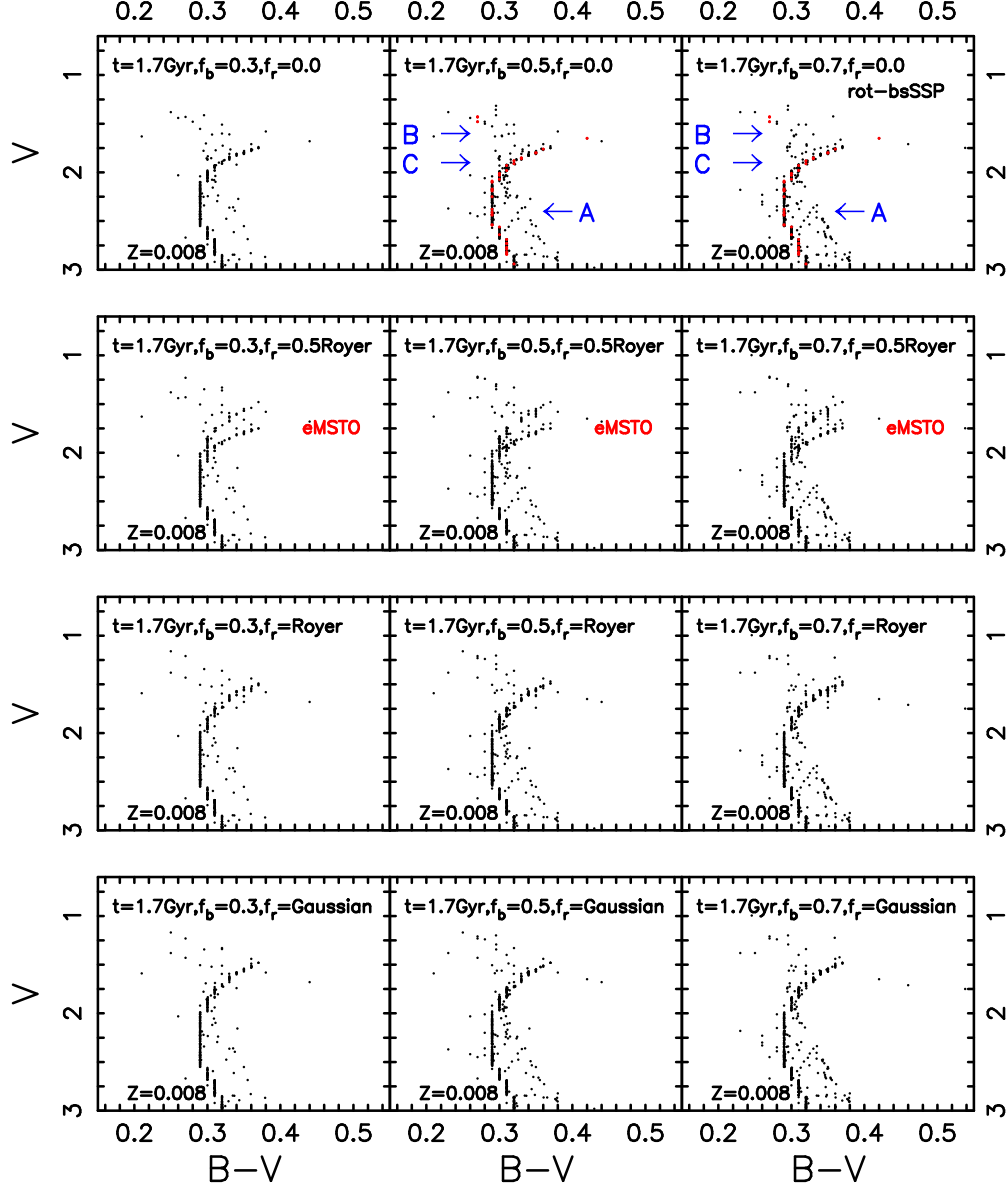


Fig. 10.— Similar to Fig. 9, but for simulated star clusters with the age of 1.7 Gyr.

unresolved binaries are not the main cause of eMSTO, although they can contribute to the eMSTOs of clusters younger than 0.5 Gyr.

## 5. EFFECT OF AGE SPREAD

In this section, we study the effect of age spread on the CMDs of star clusters with various ages. We assume that clusters form their stars within 200–500 Myrs, and the binary fractions ( $f_b$ ) of them change from 0.3 to 0.7. The ages of youngest stars in clusters are used as stellar population ages, and they are given between 0.2 and 2.5 Gyr. As some examples, the main results are presented in Figs. 11 to 17. Note that only a few separated star bursts with age interval of 100 Myr are taken for building composite stellar populations, but the star formation of real clusters could be continuous bursts. A homogeneous star formation history is assumed for all simulated clusters, although it is possibly different for real clusters. This results in separated isochrones, and the figures look somewhat differently from the CMDs caused by rotation (Figs. 3–10). In addition, the age spread of most star clusters younger than 0.8 Gyr is possibly less than about 40 per cent, but in order to supply some comparisons with older clusters, the CMDs with spreads up to 500 Myr are shown here. This is helpful for better understanding the dependence of effect of age spread on stellar age, and also the difference between the effects of age spread and rotation.

We find that age spread has a significant effect on the CMDs of all clusters younger than 2.0 Gyr (Figs. 11–16). The main effect of age spread is to thicken the main-sequence turn-off part. In detail, the turn-off of a cluster with multiple star bursts has obviously spread in both color and magnitude, which is obviously different from that of an SSP of stars with the same metallicity and age (see top panels of Figs. 3 to 10 for comparisons). As we see, the shape of CMD part consisting of main sequence and turn-off looks like a “golf-club”, if a cluster is younger than 2.0 Gyr and has age spreads larger than 200 Myr. However, we see that an age spread less than 500 Myr affects the CMDs of clusters older than about 2.5 Gyr slightly (Fig. 17). Even though an age spread of 500 Myr is assumed, the turn-offs of clusters with age of 2.5 Gyr are similar to that of simple populations if the typical observational errors ( $\sim 0.014$  mag) in color and magnitude are taken into account.

We can conclude from Figs. 11 to 17 that age spread does not obviously affect the thickness of main-sequence part below turn-off, for all ages. This is a key difference between the effects of age spread and stellar rotation, because besides turn-off part, rotation widens the main sequence fainter than turn-off, as shown in e.g., Figs. 4–6. This is possibly useful for checking whether age spread exists in clusters.



Meanwhile, we observe that age spread leads to obvious extended red clumps (eRC) (Figs. 11 and 12) for clusters younger than 0.5 Gyr. This is clearly different from the effect of stellar rotation (see Figs. 3 and 4 for comparison) and implies that we can possibly check the existence of age spread from the shapes of red clumps of star clusters.

## 6. CONCLUSION

This paper investigates the effects of stellar rotation, age spread and binary stars on the CMDs of simulated star clusters with various ages, via the ASPS technique. It appears that binary star is not the main cause of eMSTO of most clusters older than 0.5 Gyr, although a few blue stragglers and red stragglers are produced by binary evolution, and unresolved binaries widen the MS toward redder color. However, binaries seem important for the eMSTOs of younger (e.g.,  $< 0.5$  Gyr) clusters. Meanwhile, stellar rotation is able to explain, at least partially, the eMSTOs of clusters. Rotation can somewhat widen the turn-offs of clusters younger than 0.5 Gyr, and extends the turn-offs of clusters between 0.5 and 1.7 Gyrs significantly. Because the rotation effect of stars outside the mass range of  $1.6\text{--}15\text{ }M_{\odot}$  is not taken into account, this work does not study the effect of rotation on the CMDs of clusters older than 1.9 Gyr. Rotation seems difficult to form CMD shapes like “golf-club” in clusters significantly older than about 1.9 Gyr, because the turn-off stars of such clusters, which are less massive than  $1.6\text{ }M_{\odot}$ , usually rotates much more slowly, and the effect of rotation decreases with increasing age from about 1.2 Gyr (see also Brandt & Huang 2015). This agrees well with the observational result, i.e., there is little evidence for eMSTOs in clusters of 2 Gyr in age or older. If less massive stars (e.g., those between  $1.0$  and  $1.6\text{ }M_{\odot}$ ) are considered, rotation widens the main sequence part below turn-off for all simulated clusters. In addition, age spread can reproduce eMSTO for all clusters younger than 2.5 Gyr, but it does not obviously affect the thickness of main-sequence part fainter than turn-off. In particular, age spread results in “golf-club” shapes in the regions near turn-off for all clusters from about 1.0 Gyr to 2.2 Gyr (tested but not shown in this paper). It also results in a significant extension of the red clumps (eRC) of clusters younger than 0.5 Gyr. As a whole, the effects of binary stars and stellar rotation depend on stellar age, obviously.

It can be concluded that the eMSTOs of clusters younger than 0.5 Gyr possibly result from age spread or a combination of binaries and stellar rotation. The eMSTOs of older clusters may be caused mainly by age spread or stellar rotation. It is also possible that the observed features are related to all the three factors.

Although we have used a recent result of Georgy et al. (2013) to calculate the effects of rotation on luminosity and surface temperature of stars, it still remains some uncertain-

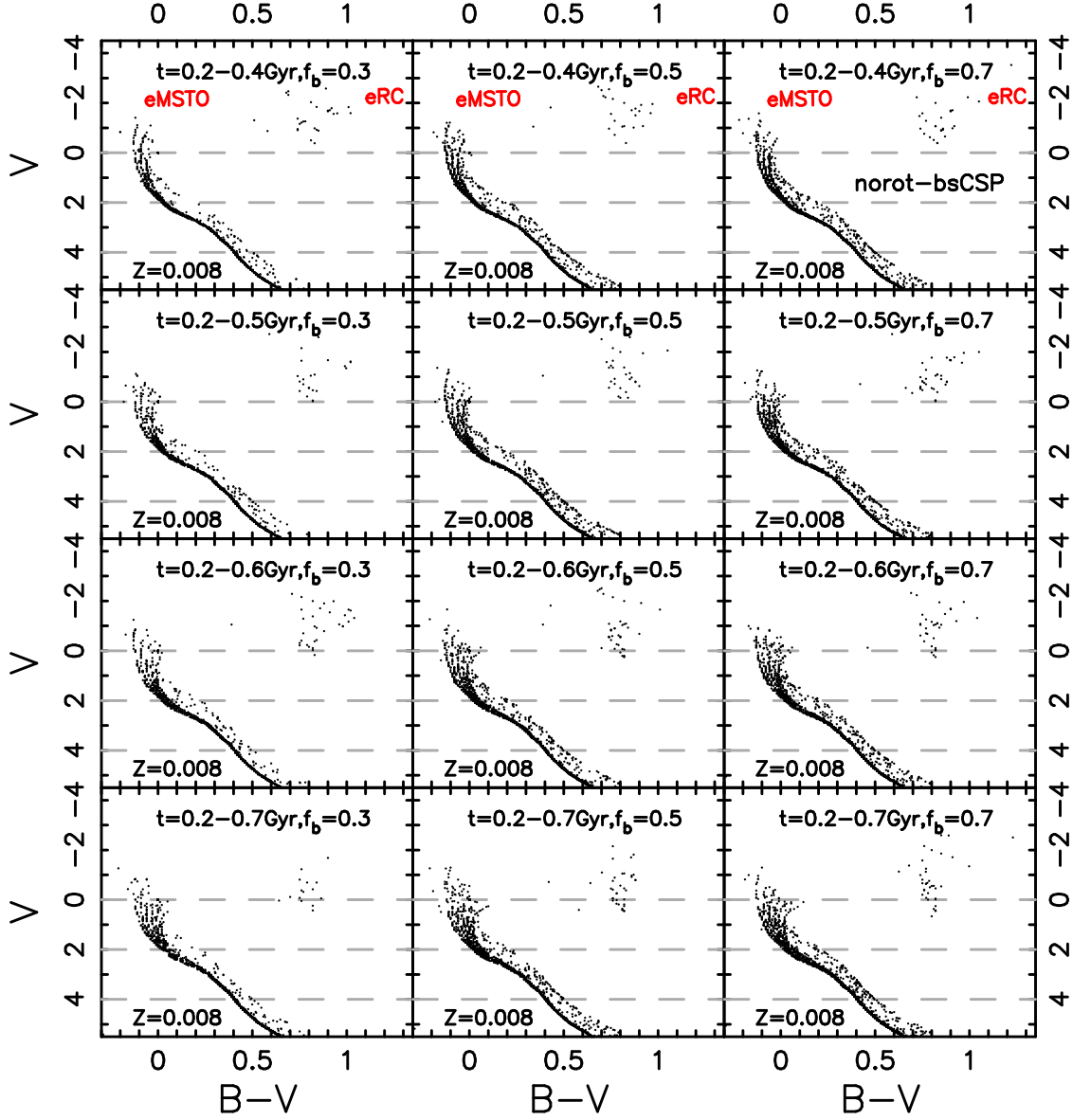


Fig. 11.— Effects of age spread and binary fraction on CMDs of simulated star clusters. All clusters have the same metallicity ( $Z = 0.008$ ). No rotating star is included in these clusters, and binaries closer than 2500 AU are assumed to be unresolved. The age of latest star burst (i.e., youngest population component), is assumed to be 0.2 Gyr. “ $t$ ” gives the age ranges of stars. From top to bottom panels, age spread is different from 200 to 500 Myr. eMSTO and eRC mean extended main-sequence turn-off and extended red clump, respectively. Binary fractions ( $f_b$ ) in left, middle, and right columns are 0.3, 0.5 and 0.7 respectively. “norot-bsCSP” means CSP consisting of non-rotating binaries and single stars.

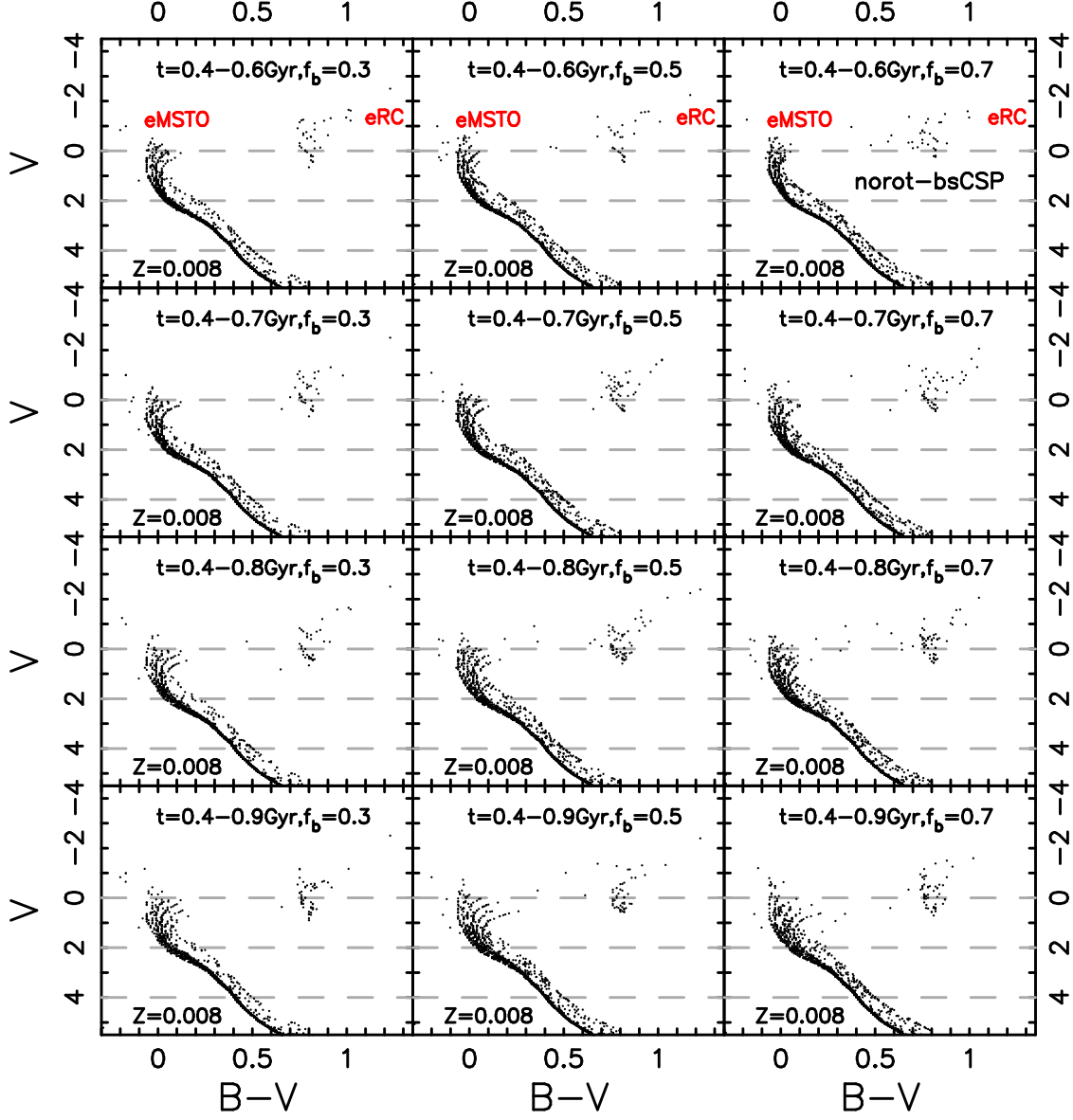


Fig. 12.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 0.4 Gyr.

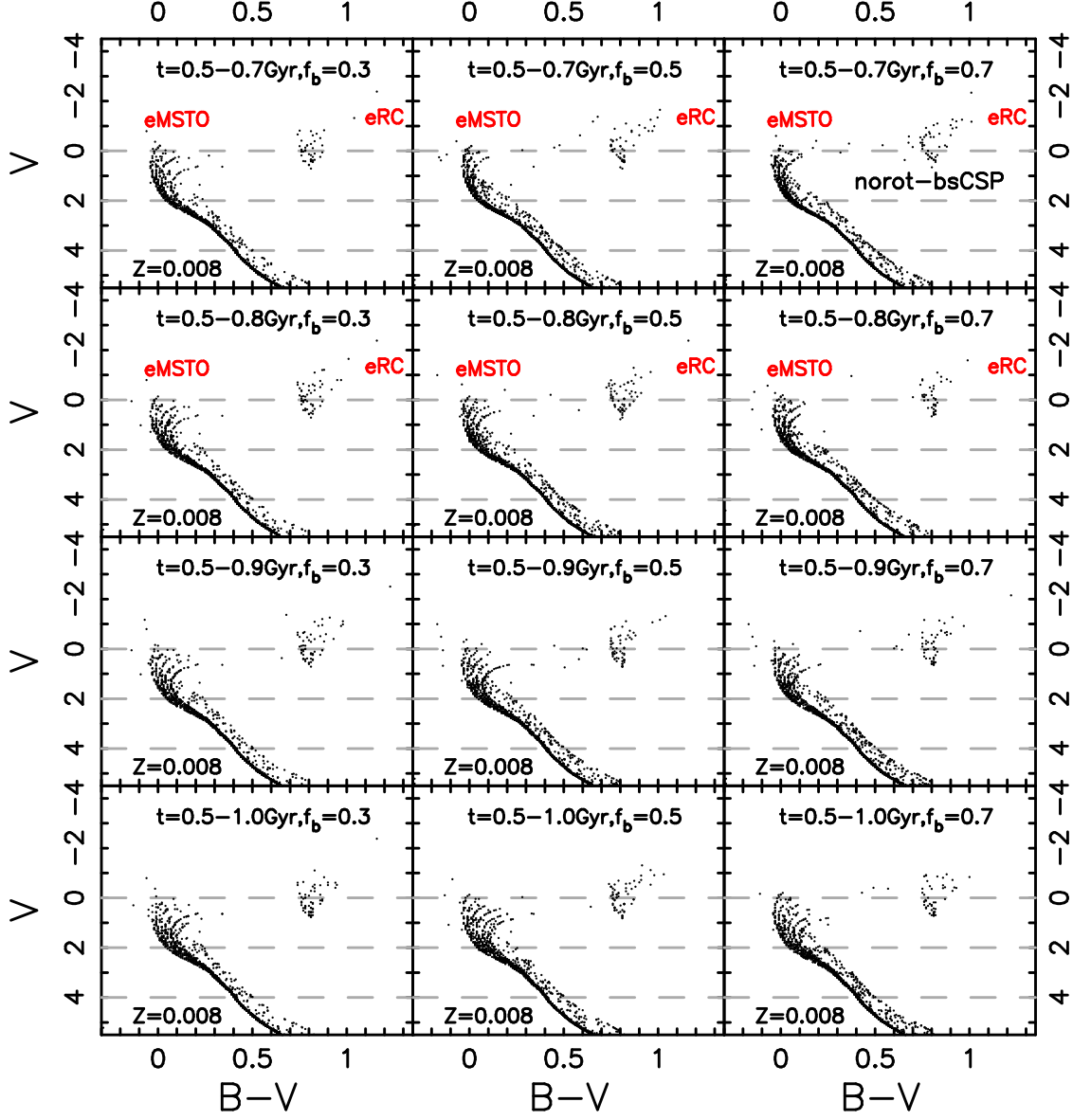


Fig. 13.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 0.5 Gyr.

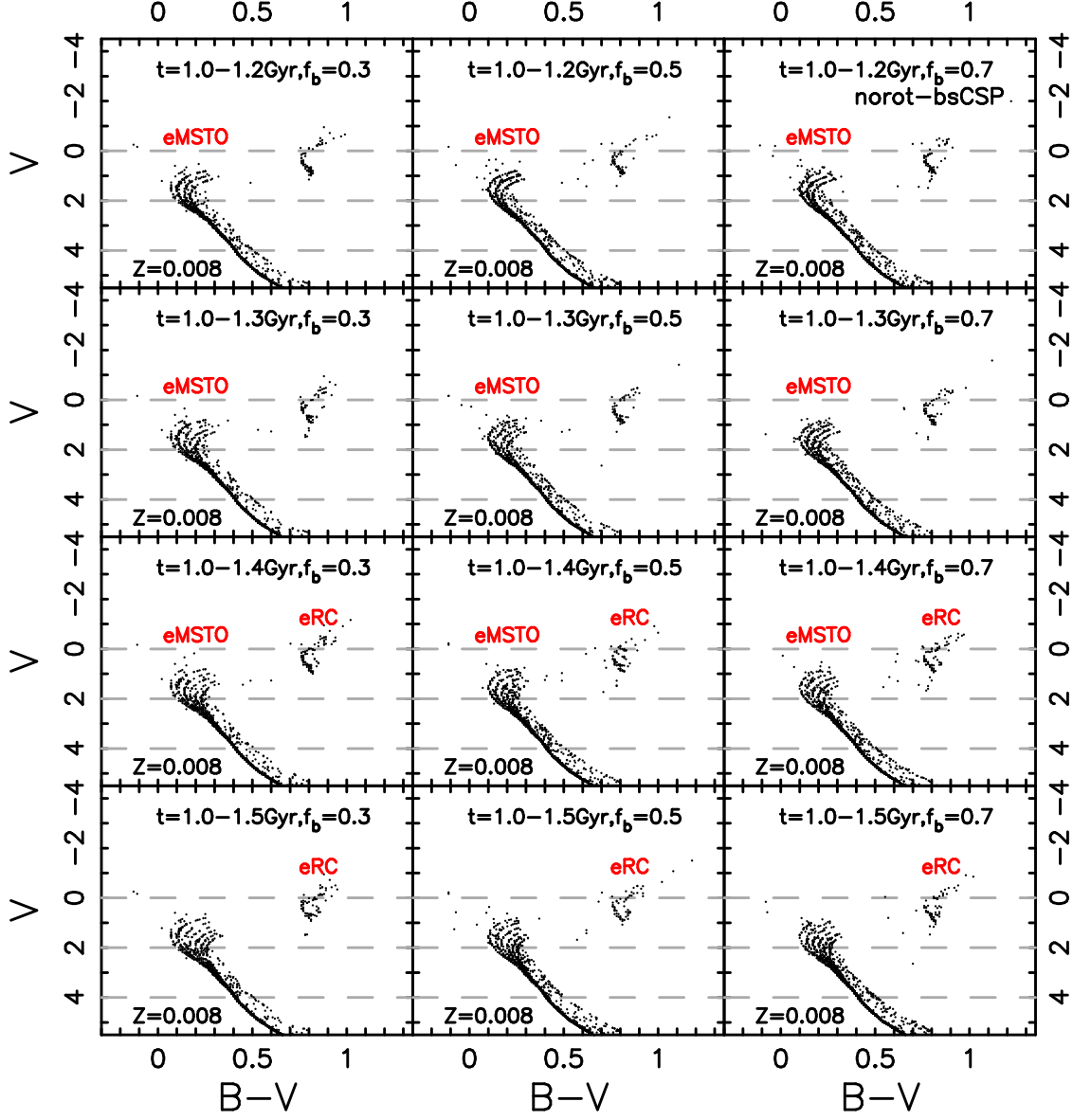


Fig. 14.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 1.0 Gyr.

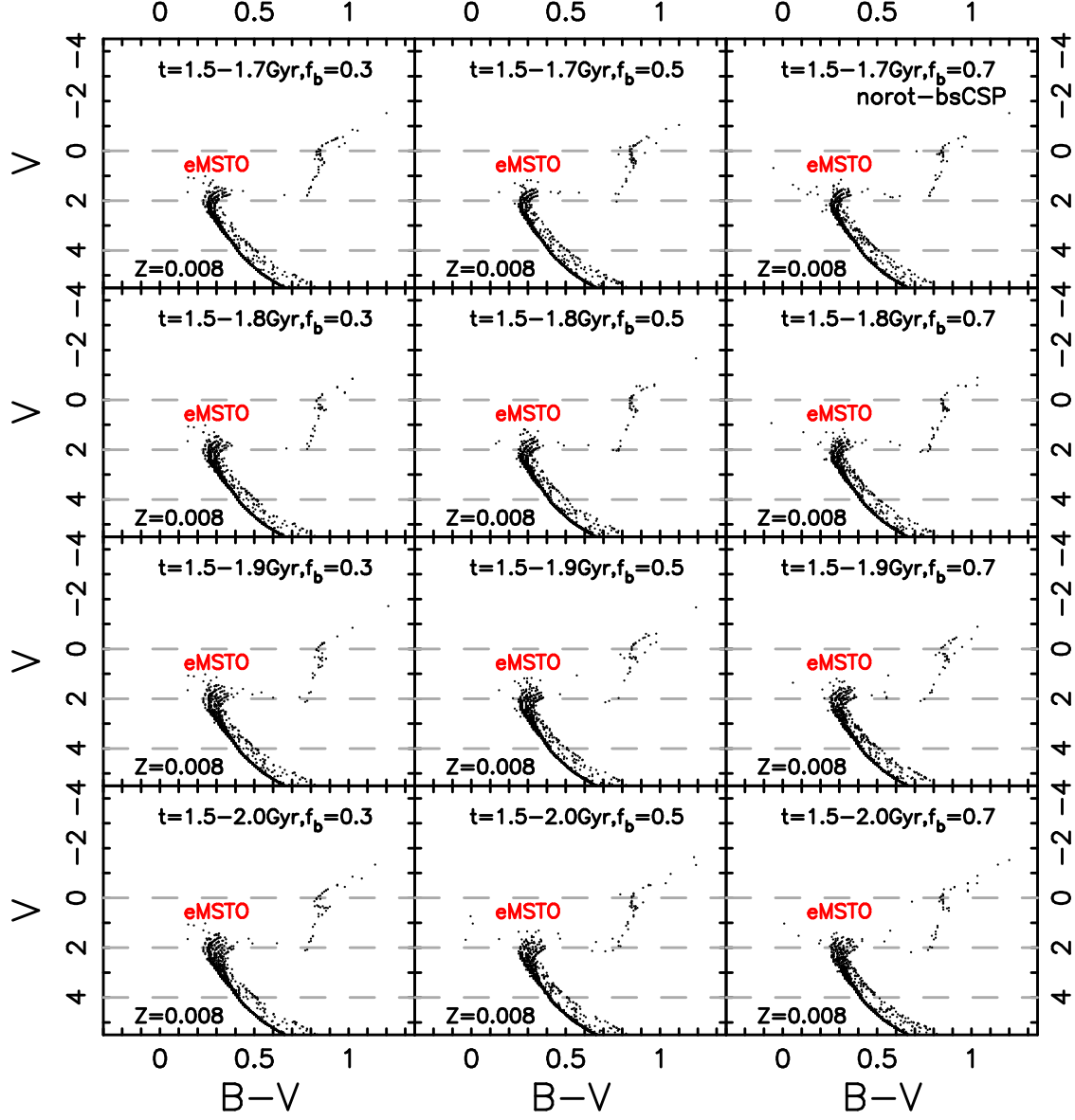


Fig. 15.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 1.5 Gyr.

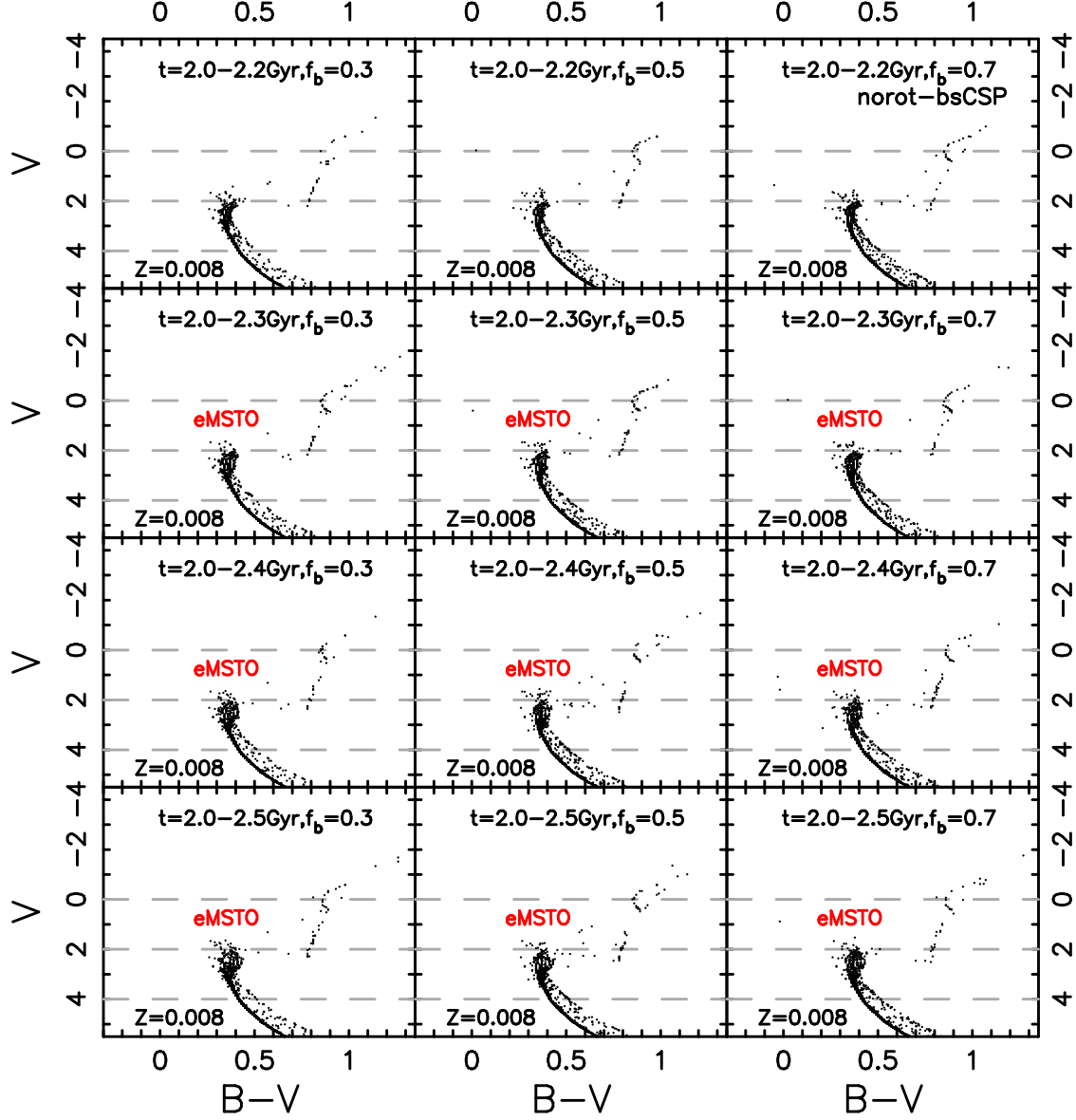


Fig. 16.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 2.0 Gyr.

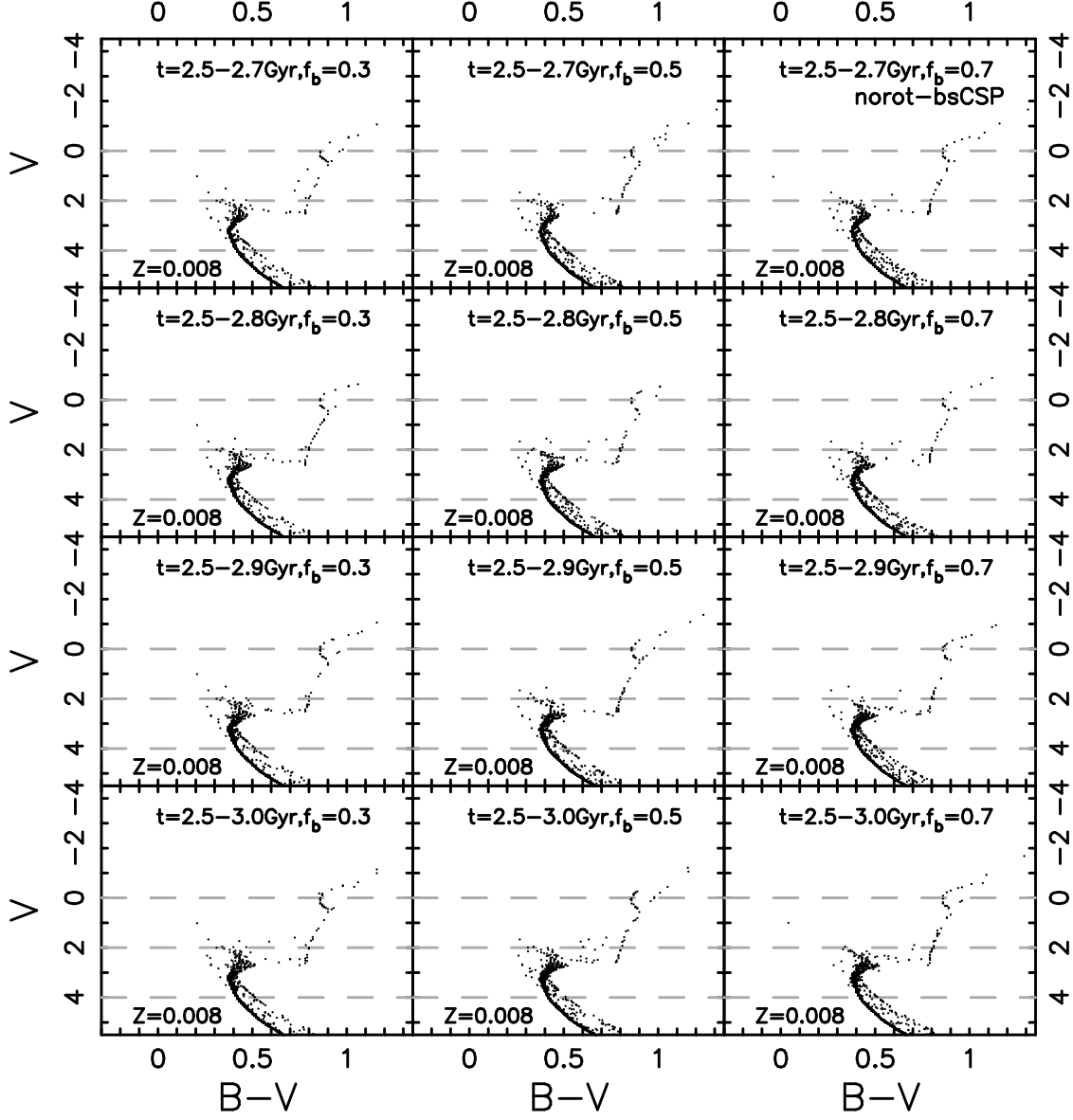


Fig. 17.— Similar to Fig. 11, but for simulated star clusters with youngest population component of 2.5 Gyr.



ties. This may somewhat affect the synthesized CMDs. **Our conclusion of effect of stellar rotation agrees well with recent works such as Brandt & Huang (2015), Niederhofer et al. (2015) and Milone et al. (2016).** Even if another database of rotating stars, Ekström et al. (2012), is used instead of Georgy et al. (2013), the results will be similar, because the two databases are from the same code. Note that although the works of Bastian & de Mink (2009), Ekström et al. (2012), and Georgy et al. (2013) suggest the possibility of rotation to explain eMSTOs of star clusters, the rotation effect of two recent works, i.e., Ekström et al. (2012) and Georgy et al. (2013) is different from Bastian & de Mink (2009) (see Brandt & Huang 2015). Besides the stellar evolutionary models, RRD affects the final CMDs evidently. This calls for accurate distributions for clusters in LMC and SMC. Moreover, this work considers the effects of binaries and rotating stars separately, but they are actually related. Although such treatment is reasonable by now due to the lack of a stellar evolutionary code, in which both binaries and rotation have been taken into account, it is certainly necessary to check the results using some new codes in the future.

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